



NRL/MR/7210--04-8773

LOFAR Scientific Memorandum #6: The LOFAR Site and Its Impact on the Key Astronomical Projects

T. JOSEPH W. LAZIO

A. S. COHEN

P. C. CRANE

K. W. WEILER

*Radio/IR/Optical Sensors Branch
Remote Sensing Division*

June 21, 2004

Approved for public release; distribution is unlimited.

20040903 093

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 21 June 2004		2. REPORT TYPE Memorandum report		3. DATES COVERED (From - To) October 2003-Present	
4. TITLE AND SUBTITLE LOFAR Scientific Memorandum #6: The LOFAR Site and Its Impact on the Key Astronomical Projects				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 61153N	
6. AUTHOR(S) T. Joseph W. Lazio, A.S. Cohen, P.C. Crane, and K.W. Weiler				5d. PROJECT NUMBER SP034 06 4A	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER 8418-00	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory, Code 7210 4555 Overlook Avenue, SW Washington, DC 20375-5320				8. PERFORMING ORGANIZATION REPORT NUMBER NRL/MR/7210--04-8773	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 800 North Quincy Street, BCT 1 Arlington, VA 22217-5660				10. SPONSOR / MONITOR'S ACRONYM(S) ONR	
				11. SPONSOR / MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT We consider the impact of potential LOFAR sites on the key astronomical projects set for the telescope. We compare the sites on the basis of the total fraction of the sky accessible and on the basis of the total fraction of the Galactic plane accessible. The former criterion is most important for extragalactic studies while the latter criterion is most important for studies of the Milky Way. Of the three sites, the Netherlands, the Southwest United States, and Western Australia, we find that Western Australia provides both the largest fraction of the sky accessible and the largest fraction of the Galactic plane accessible, followed by the Southwest United State and the Netherlands, in that order. This analysis has been conducted independently of the work of the LOFAR Site Evaluation Committee (SEC) and has not been reviewed by nor is it endorsed by that body.					
15. SUBJECT TERMS Radio Astronomy; Radio Interferometry					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 18	19a. NAME OF RESPONSIBLE PERSON Joseph Lazio
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) (202) 404-6329

CONTENTS

EXECUTIVE SUMMARY	1
1. INTRODUCTION	1
2. ACCESSIBLE SKY FRACTION	2
3. ACCESSIBLE GALACTIC PLANE FRACTION	3
4. SKY OVERLAP	9
5. CONCLUSIONS	15

EXECUTIVE SUMMARY

We consider the impact of potential LOFAR sites on the key astronomical projects set for the telescope. We compare the sites on the basis of the total fraction of the sky accessible and on the basis of the total fraction of the Galactic plane accessible. The former criterion is most important for extragalactic studies while the latter criterion is most important for studies of the Milky Way. Of the three sites, the Netherlands, the Southwest United States, and Western Australia, we find that Western Australia provides both the largest fraction of the sky accessible and the largest fraction of the Galactic plane accessible, followed by the Southwest United States and the Netherlands, in that order.

This analysis has been conducted independently of the work of the LOFAR Site Evaluation Committee (SEC) and has not been reviewed by nor is it endorsed by that body.

THE LOFAR SITE AND ITS IMPACT ON THE KEY ASTRONOMICAL PROJECTS

1. INTRODUCTION

The Low Frequency Array (LOFAR) project has identified four key astronomical goals:

- The High Redshift Universe: Study the most distant radio galaxies and quasars;
- The Epoch of Reionization (EoR): Detect the global signature and map the structures in the transition phase from a cold, dark Universe to the current photoionized era;
- Acceleration, Turbulence, & Propagation in the Interstellar Medium: Develop a 3-dimension model for the magnetoionic medium of the Galaxy;
- The Bursting and Transient Universe: Detect short-lived transient events such as supernovae, gamma-ray bursts, bursts from Jupiter-like planets, and merging and interacting compact objects.

A fifth key scientific project—Solar-Terrestrial Relationships: Detect coronal mass ejections, possibly in combination with a solar radar, and study the Earth's ionosphere—has been identified as well, though we shall not address it explicitly in this memo.

Concurrently, the LOFAR Site Evaluation Committee has identified three sites willing and able to host LOFAR:

- The Netherlands (NL): Most likely centered on the northern province of Drenthe, but encompassing most of the country and possibly portions of northern Germany, with an approximate latitude of $+52^\circ$;
- The southwest United States (US): Most likely centered in the State of New Mexico, but possibly including western portions of the State of Texas, with an approximate latitude of $+34^\circ$; and
- Western Australia (WA): Multiple sites have been identified within the State of Western Australia, but all have an approximate latitude of -26° .

The location of the site has ramifications for the various key scientific projects. In this memorandum, we shall develop three criteria for evaluating the astronomical suitability of potential telescope sites and apply them to the proposed LOFAR sites. Because LOFAR is planned as an aperture synthesis instrument, the u - v coverage is also important, and we shall present examples showing the u - v coverage for the proposed sites. We anticipate that our criteria may be applicable

Table 1—LOFAR Sky Coverage				
Site	Fractional Sky Coverage	Declination Coverage	Fractional Galactic Plane Coverage	Galactic Longitude Coverage
NL	75%	-21° – $+90^{\circ}$	59%	17° – 229°
US	87%	-42° – $+90^{\circ}$	73%	-8° – 254°
WA	91%	-90° – $+57^{\circ}$	79%	-199° – 85°

Notes.—All values assume an antenna element sensitivity and mapping capability to the -15 dB point on the antenna power pattern.

more broadly, e.g., to the choice of a site for the Square Kilometer Array (SKA). In §2 we consider the total fraction of the sky accessible to the telescope, in §3 we consider the fraction of the Galactic plane accessible to the telescope, in §4 we consider the fraction of the sky visible to LOFAR that overlaps with the fraction of the sky visible to other current and planned large telescopes, and in §5 we present our conclusions. The results are summarized in Table 1 as well.

In all of our work we have assumed that the LOFAR antenna elements (i.e., dipoles) have a 60° FWHM power pattern. Where we have modeled the u - v coverage produced by LOFAR, we have assumed that it has 99 stations, distributed in a logarithmic spiral, over 400 km. The array is assumed to be centrally condensed with a radial density profile scaling like $r^{-3.4}$, consistent with various specifications that place 25% of the total collecting area within the central 2 km. Figure 1 shows the assumed station layout for LOFAR and the snapshot u - v coverage for a source at the zenith.

Furthermore, we have not taken into account any local obstructions of the horizon, e.g., mountains, trees, etc. Thus, the results presented here should be seen as a “best-case” scenario.

2. ACCESSIBLE SKY FRACTION

Our first criterion is the accessible sky fraction, i.e., the fraction of the 4π steradians of the sky that the telescope can observe above some sensitivity limit. This criterion is motivated by the desire to see as many objects as possible.

Because the Universe is homogeneous and isotropic, this criterion impacts the High-Redshift Universe and the EoR key projects. If there is a population of extragalactic transients (e.g., gamma-ray bursts), then this criterion also impacts the Transient and Bursting Universe key project.

As a figure of merit for sky coverage, we have chosen the effective integration time available to the telescope in units of the integration time at the zenith. The effective integration time is the product of the antenna element gain and the hour angle over which a source at a given declination can be observed. At the zenith, an antenna element is assumed to have a gain of unity. In general, as the zenith angle increases, both the gain of the antenna element and the hour angle that a source is above the horizon decrease.

Figure 2 presents sensitivity-weighted images of the sky accessible at the three sites. The sky is shown in a Hammer-Aitoff projection with 0^{h} right ascension at the center of the plot and right

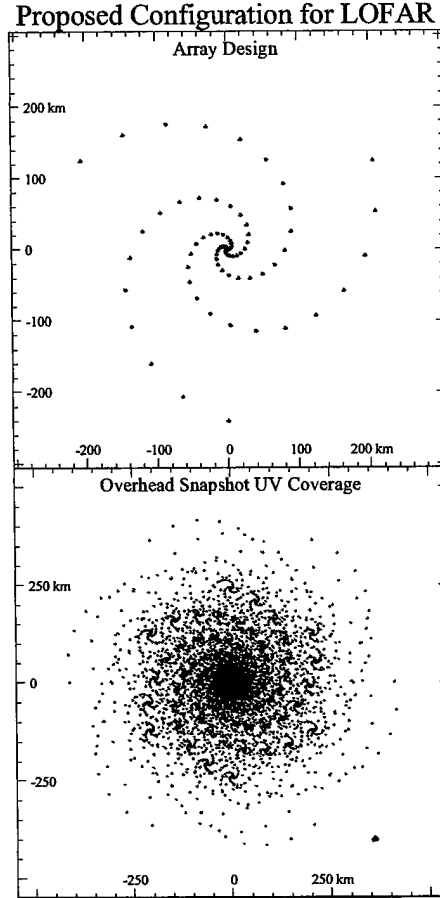


Fig. 1—*Top*: The assumed station layout for LOFAR, as used in simulations presented in this memo. *Bottom*: The u - v coverage resulting from the assumed station layout for a source at the zenith.

ascension increasing to the left. A solid black line indicates the Galactic plane, and a cross indicates the position of the Galactic center. Areas shaded green indicate the region of the sky for which the effective integration time is larger than 60 min., areas shaded yellow indicate the region of the sky for which the effective integration time is between 5 and 60 min., and areas shaded red indicate the region of the sky for which the effective integration time is less than 5 min.

Table 1 summarizes the total sky coverage accessible to a telescope at each site, as a fraction of the 4π steradians in the entire sky. Also listed is the declination coverage for each site, for which the effective integration time is larger than 5 min.

Figure 3 presents the corresponding u - v coverage for these sites for sources at various declinations. We have not produced a quantitative figure of merit for characterizing the u - v coverage akin to the fraction of the sky covered. Qualitatively, though, the fraction of the sky over which a circular or near-circular beam is achieved is largest for WA, followed by the US and NL, in that order.

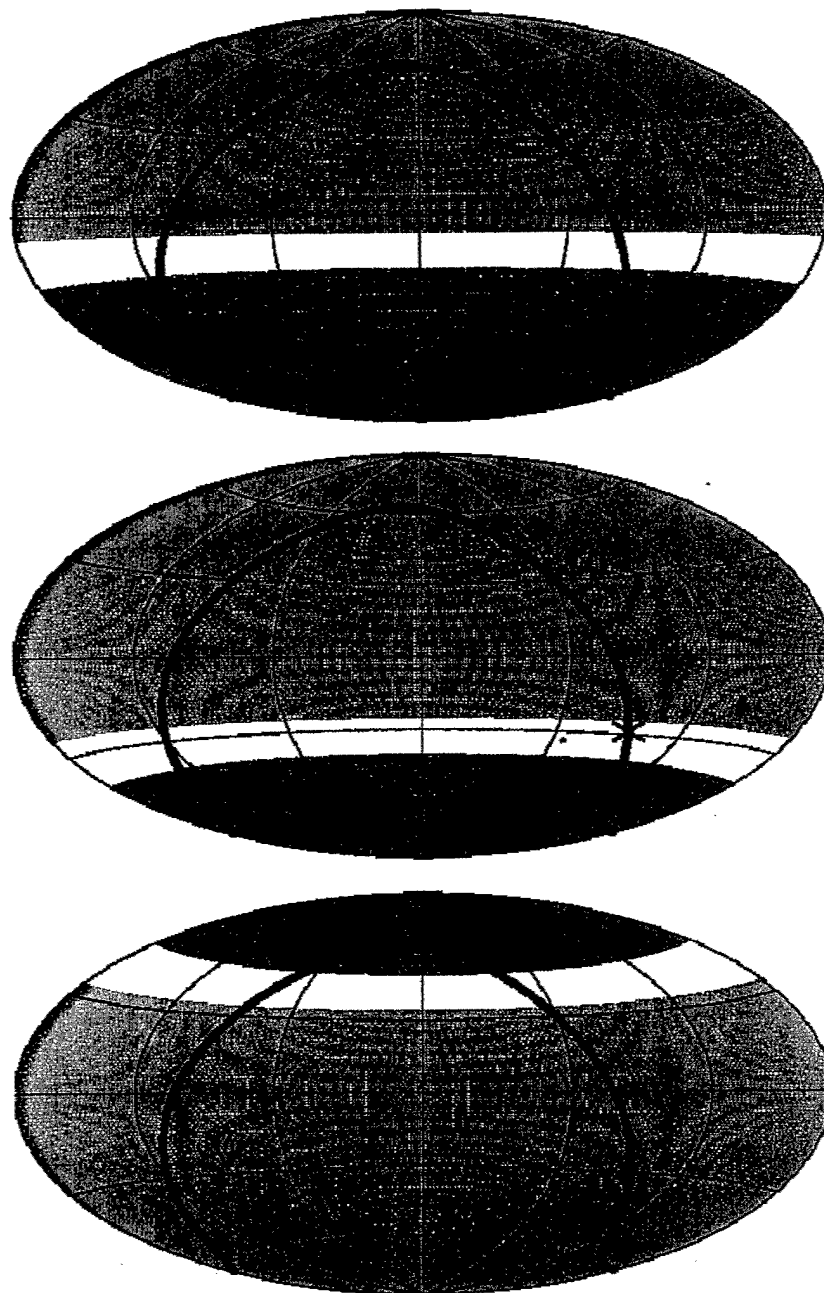


Fig. 2—Sensitivity-weighted image of the sky accessible to the three possible sites. See text for additional details. *Top* NL site; *Middle* US site; and *Bottom* WA site.

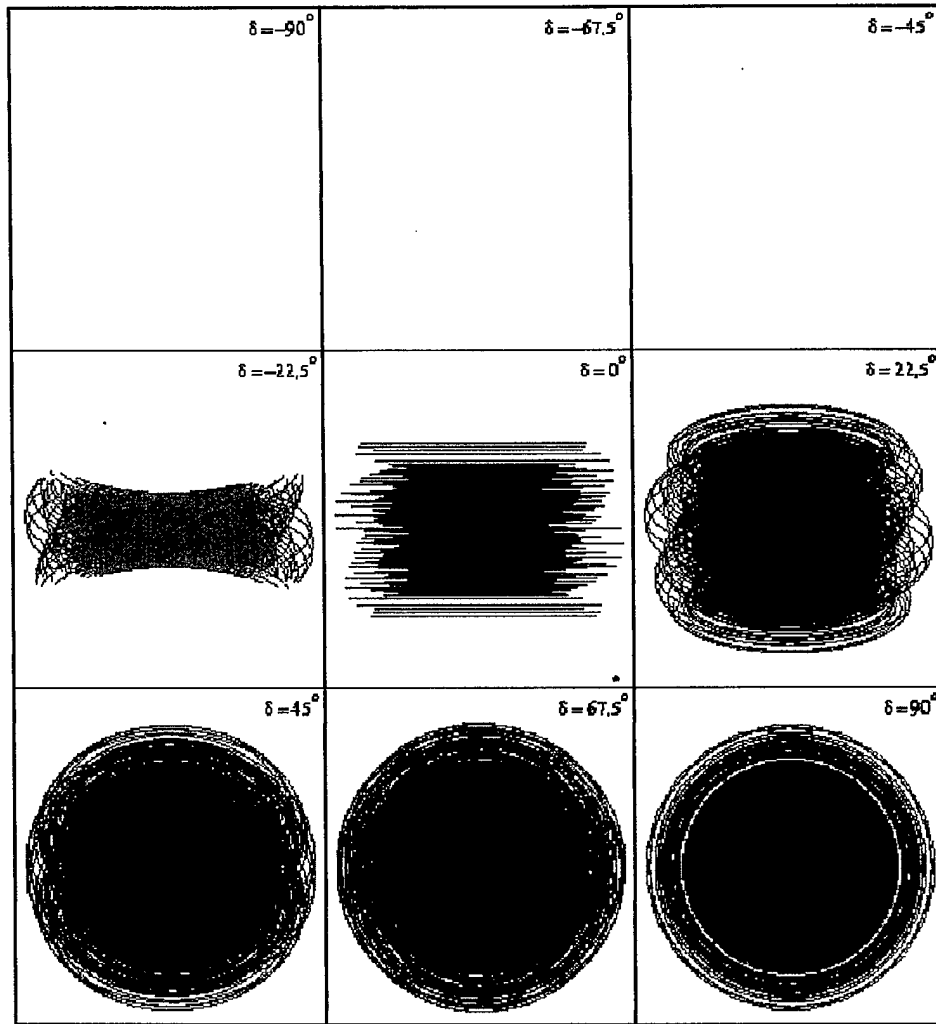


Fig. 3—The u - v coverage obtained for sources at various declinations assuming a station layout as shown in Figure 1 and located at the NL site. The u - v coverage is produced for a full synthesis observation; tracks through the u - v plane are shown in red for elevations between 7° and 30° and in blue for elevations above 30° .

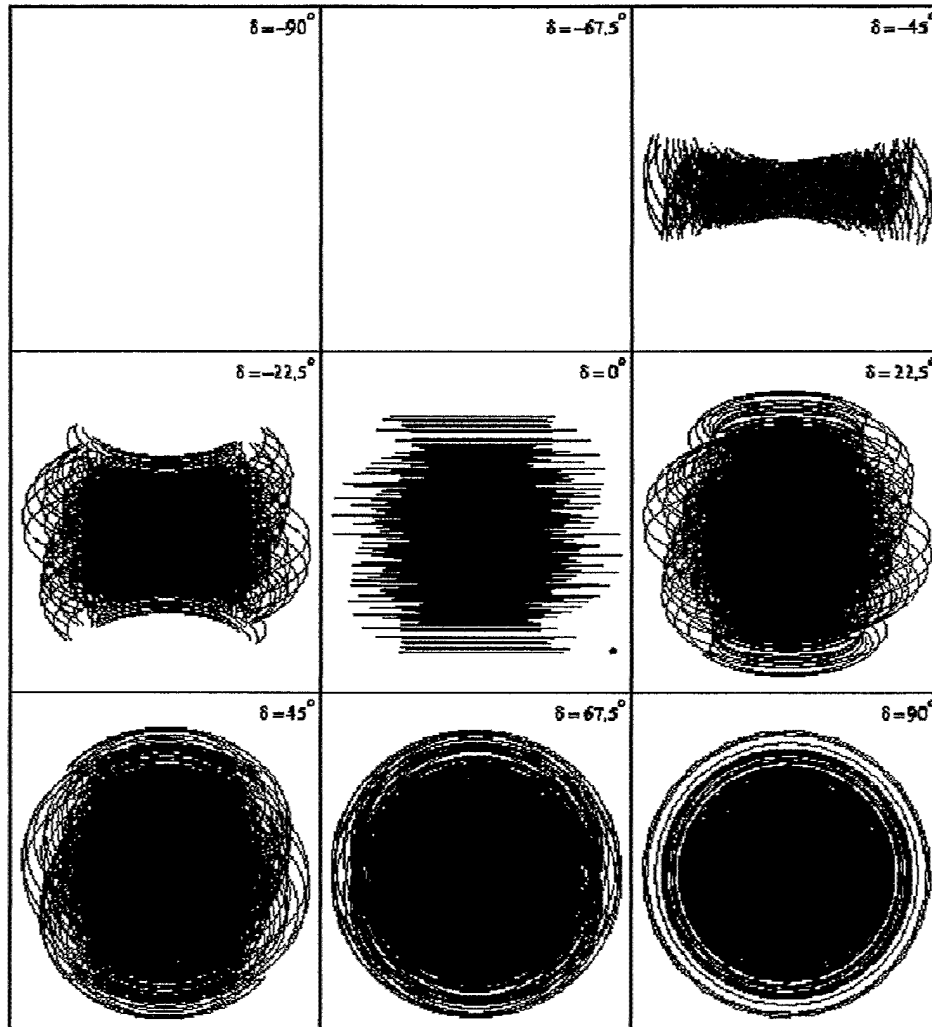


Fig. 3—(cont) $u-v$ tracks at the proposed US site.

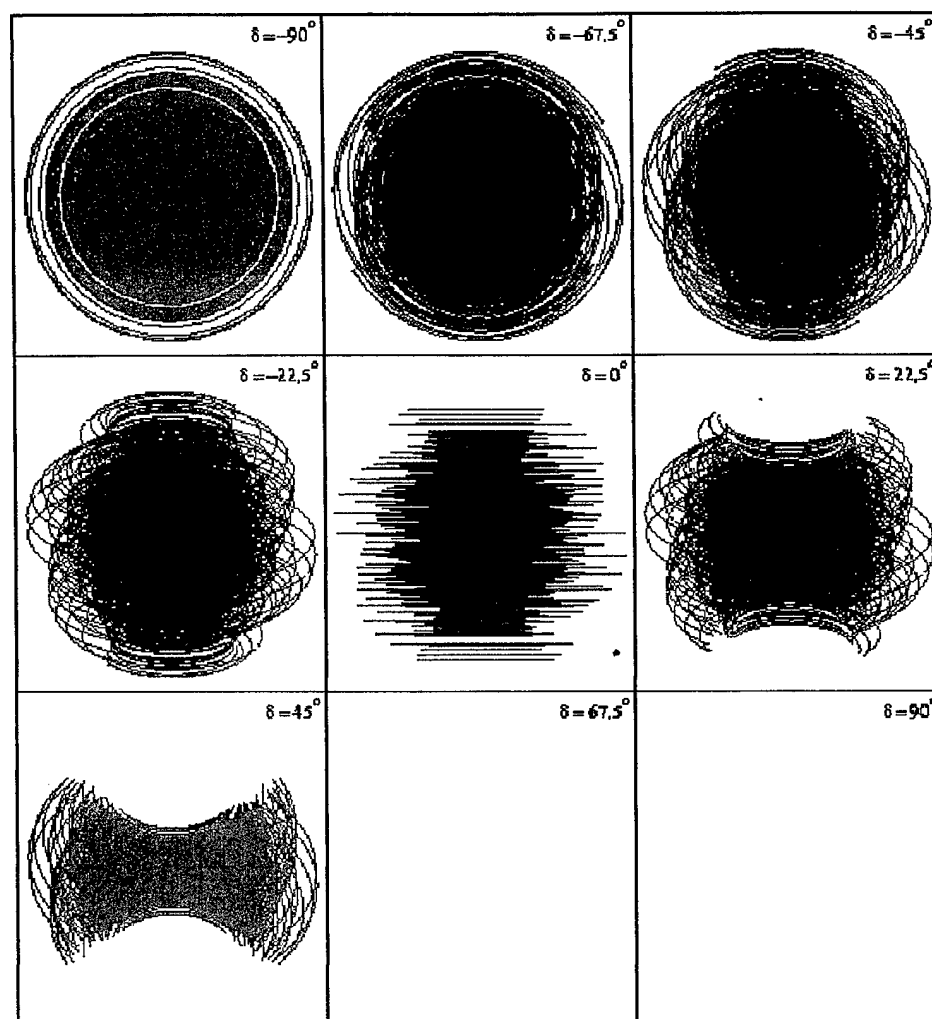


Fig. 3—(cont) $u-v$ tracks at the proposed WA site.

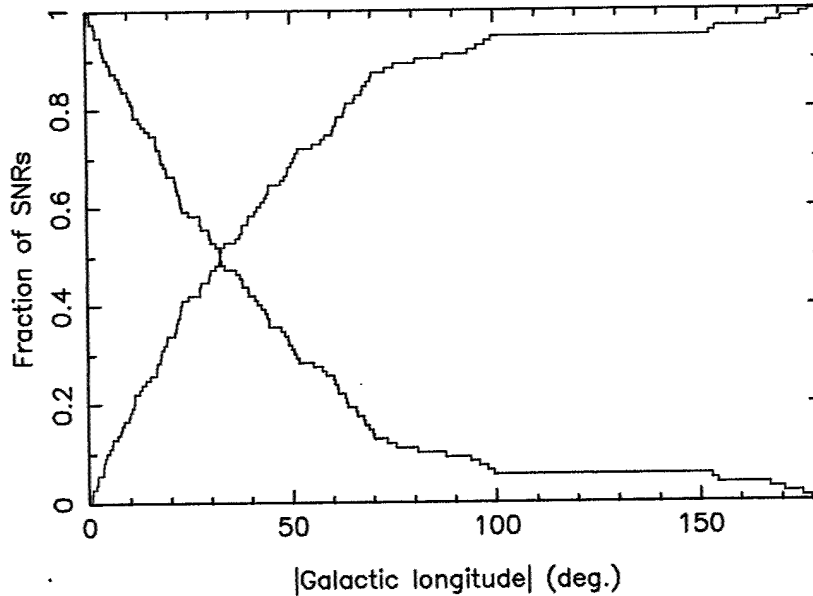


Fig. 4—The cumulative distribution functions of supernova remnants as a function of (absolute) Galactic longitude. The green curve shows the fraction of SNRs *interior* to a given Galactic longitude, while the red curve shows the fraction of SNRs *exterior* to a given longitude.

3. ACCESSIBLE GALACTIC PLANE FRACTION

Our second criterion is the fraction of the Galactic plane accessible to the telescope. This criterion is motivated by the Acceleration, Turbulence, & Propagation and the Bursting and Transient Universe key projects. The former project involves probing lines of sight through the Milky Way. For the latter project, there is a known Galactic population of radio transients, radio counterparts to X-ray bursts from compact binaries, that is concentrated toward the inner Galaxy (Fender & Kuulkers 2001; R. Fender 2002, private communication); to the extent that there are unknown populations of Galactic transients, they probably also follow the general stellar distribution in being concentrated toward the inner Galaxy.

As an indication of the longitude range that needs to be covered by LOFAR, we consider the distribution of supernova remnants (SNRs). We choose SNRs because they are a Galactic population of objects likely to be seen with LOFAR. Figure 4 shows the cumulative distribution function of SNRs as a function of Galactic longitude, for those SNRs listed in the catalog by Green (2001). We see that 50% of all SNRs are found at longitudes $|\ell| < 30^\circ$ and that 90% of all SNRs are found at longitudes $|\ell| < 70^\circ$.

Figure 5 presents the fraction of the Galaxy accessible to a telescope at each of the three sites. In each figure the green shaded region indicates the region accessible to the telescope, with yellow lines indicating the extreme limits in Galactic longitude. As an indication of Galactic structure, the spiral arms and molecular ring are shown, as modeled in the Taylor & Cordes (1993) model for the Galactic distribution of the ionized interstellar medium; the shape and location of the spiral arms and molecular ring are intended for illustrative purposes only and not as a detailed model

NL LOFAR Galactic Coverage

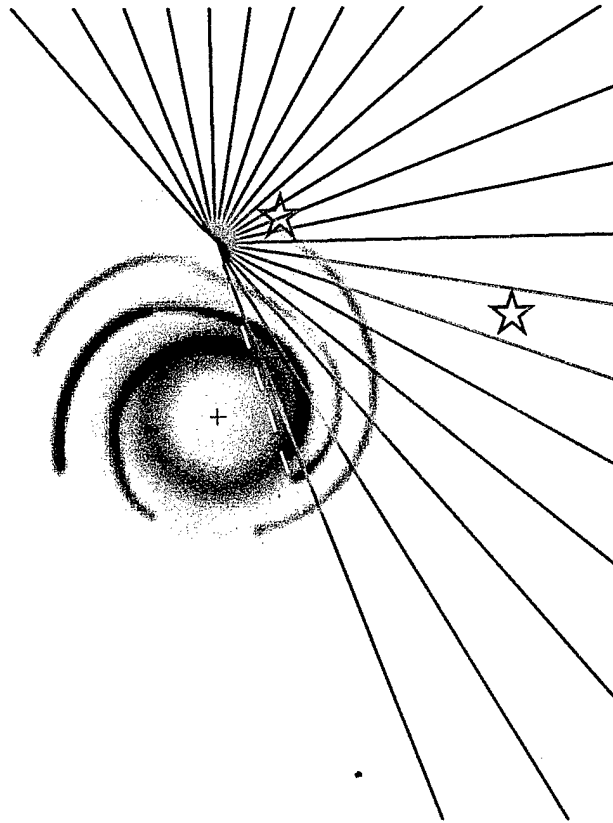


Fig. 5—The fraction of the Galaxy accessible to the NL site. See text for additional details.

of Galactic structure. Red stars mark the locations of the sources Cas A and Cyg A; the latter is taken to be 15 kpc distant to give an indication of its direction, if not distance.

Figure 6 shows the u - v coverage obtained for sources at different Galactic longitudes, focussing on sources toward the inner Galaxy. Again, we have not produced a quantitative measure of the u - v coverage. Nonetheless, it is clear that the WA site will be able observe the largest fraction of the inner Galaxy with the most nearly circular beam, followed by the US and the NL sites, in that order.

4. SKY OVERLAP

Many of LOFAR's key scientific projects will require or be aided by observations at other wavelengths. For instance, detecting high-redshift radio galaxies requires optical or infrared observations to obtain redshifts of candidate objects.

Table 2 presents the overlap between LOFAR and a number of current or planned (ground-

US LOFAR Galactic Coverage

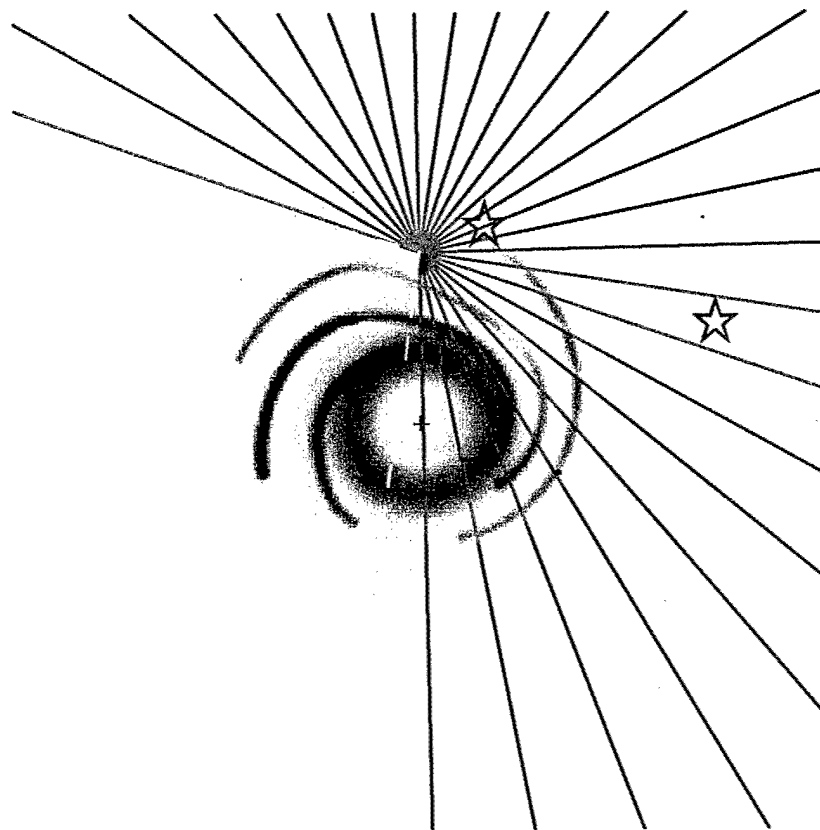


Fig. 5—(cont) The fraction of the Galaxy accessible to the US site.

WA LOFAR Galactic Coverage

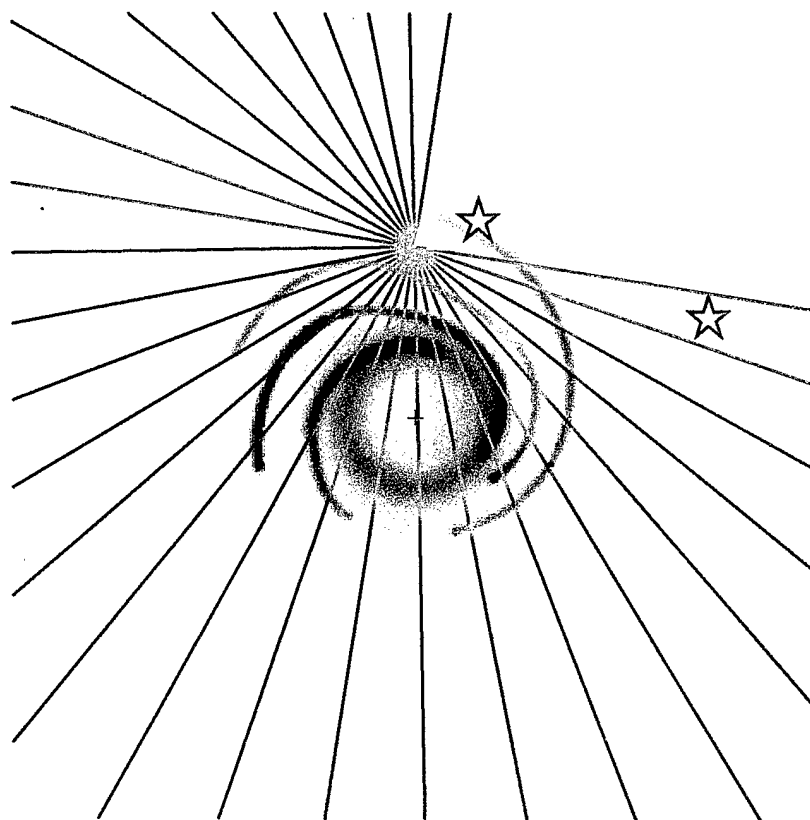


Fig. 5—(cont) The fraction of the Galaxy accessible to the WA site.

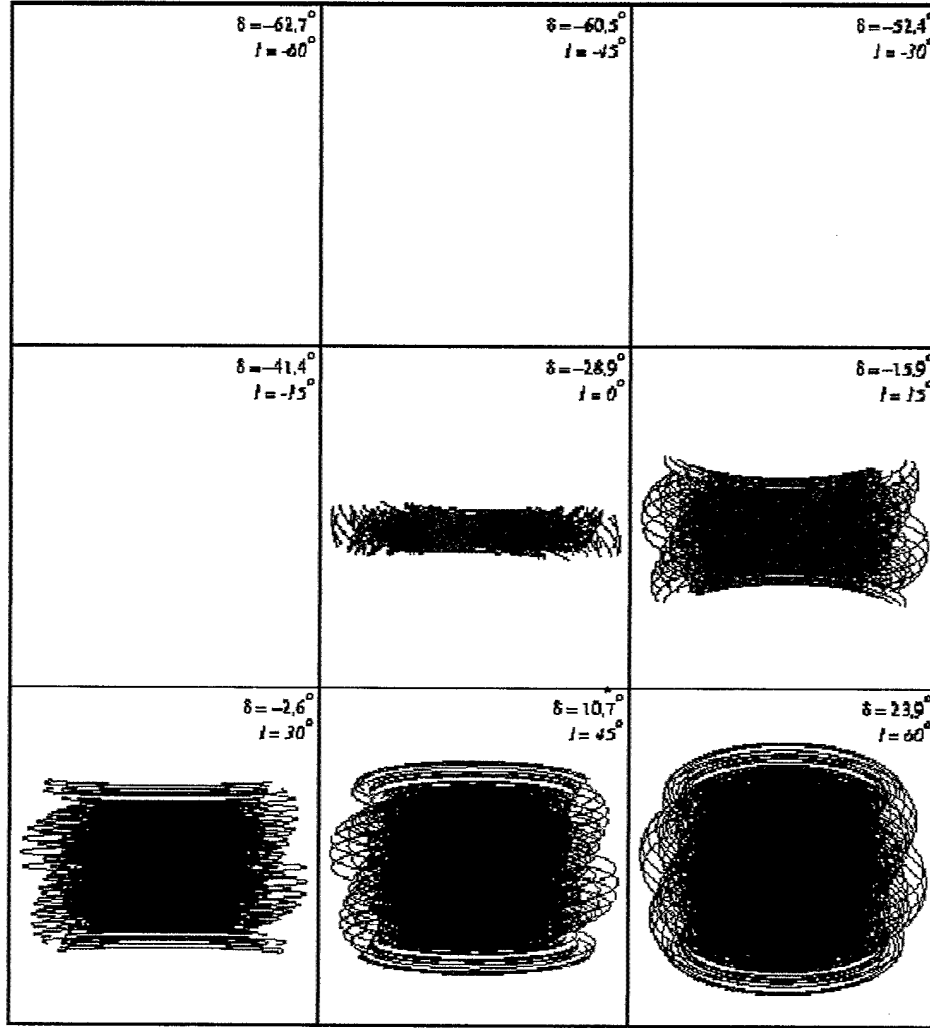
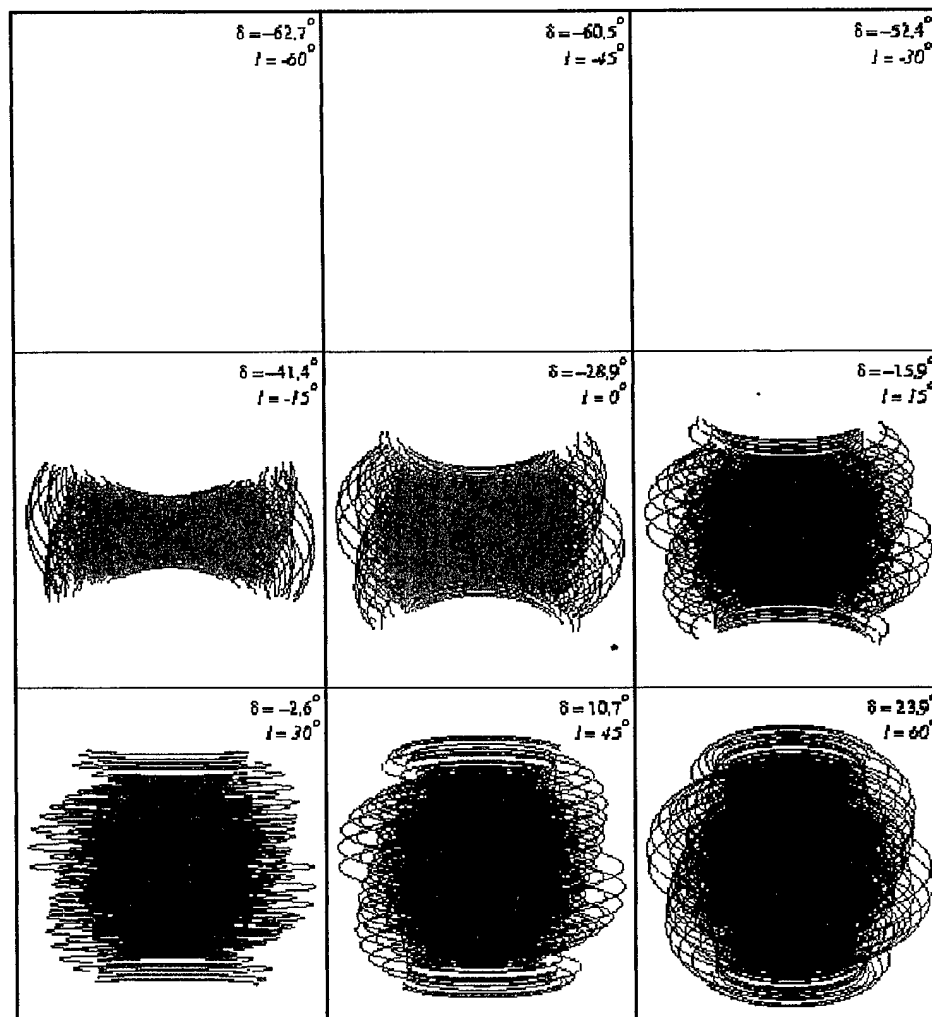


Fig. 6—The u - v coverage obtained for sources at various Galactic longitudes toward the inner Galaxy, assuming a station layout such as that shown in Figure 1 and located in NL. The u - v coverage is produced for a full synthesis observation; tracks through the u - v plane are shown in red for elevations between 7° and 30° and in blue for elevations above 30° .

Fig. 6—(cont) u - v tracks for the proposed US site.

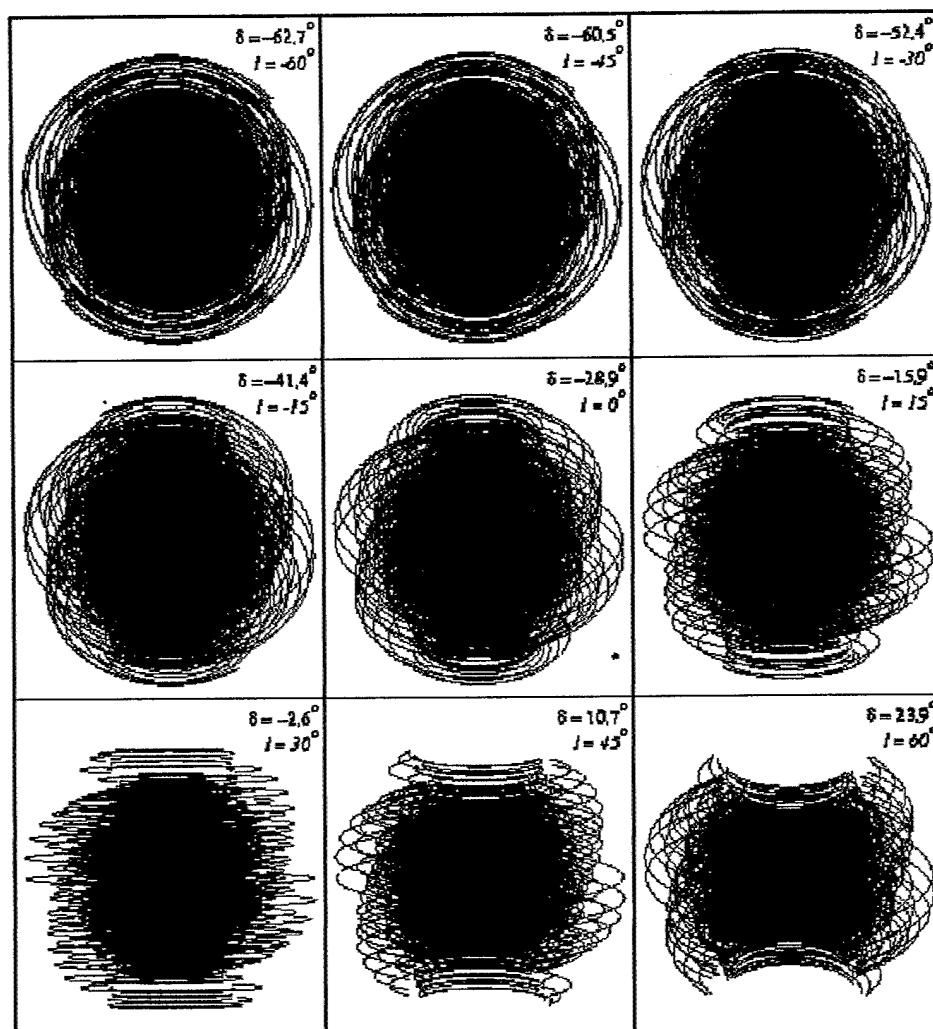


Fig. 6—(cont) $u-v$ tracks for the proposed WA site.

Table 2—LOFAR Sky Overlap with Other Telescopes

Site		NL	US	WA
	Latitude	52.5	34.1	−26.7
Fractional Overlap				
AAO	−31	0.50	0.61	0.86
ATCA	−30	0.50	0.61	0.86
ALMA	−23	0.55	0.66	0.88
VLT	−25	0.54	0.65	0.88
Keck	20	0.73	0.84	0.72
Palomar	33	0.73	0.84	0.64
VLA	34	0.73	0.84	0.63
WSRT	52	0.73	0.84	0.52

based) large telescopes, assuming that LOFAR can observe to the -15 dB power point on the antenna elements. This list is not intended to be exhaustive, merely illustrative. Nonetheless, it is clear that mid-latitude sites (US and WA) offer more overlap with other telescopes than does the NL site; the two mid-latitude sites are nearly identical, with the US site offering a mean overlap of 74% with the various other telescopes while the WA site offering a mean overlap of 75%. Indeed, a *larger* fraction of the WSRT sky is available to the US site than to the NL site. This apparently contradictory result occurs because the WSRT elements are fully steerable, while the LOFAR elements are not.

5. CONCLUSIONS

Using the criteria of total sky accessible and fraction of the Galactic plane accessible, we have shown how the three sites in contention for LOFAR siting compare. The site with the largest fraction of the total sky accessible and with the largest fraction of the Galactic plane accessible is Western Australia, followed by the southwest US, followed by the Netherlands. Similar conclusions follow when considering overlap between LOFAR and other existing and planned large telescopes. The largest fractional overlap is obtained from the Western Australia site followed by the US and NL sites in that order.

Tables 1 and 2 summarize our results.

6. BIBLIOGRAPHY

- Fender, R. P.; Kuulkers, E. 2001, "On the Peak Radio and X-ray Emission from Neutron Star and Black Hole Candidate X-ray Transients," *Mon. Not. R. Astron. Soc.*, **324**, 923
- Green, D. A. 2001, "A Catalogue of Galactic Supernova Remnants (2001 December version)", Mullard Radio Astronomy Observatory, Cavendish Laboratory, Cambridge, United Kingdom; <http://www.mrao.cam.ac.uk/surveys/snrs/>
- Taylor, J. H. & Cordes, J. M. 1993, "Pulsar Distances and the Galactic Distribution of Free Electrons," *Astrophys. J.*, **411**, p. 674